Measurement of cross sections in vector-boson scattering processes: $W^{\pm}W^{\pm}$ production cross section measurement with the ATLAS detector @ $\sqrt{s} = 8$ TeV and 13 TeV prospects

Giulia Gonella
Albert-Ludwigs-Universität Freiburg

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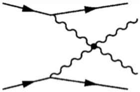
VBS analyses

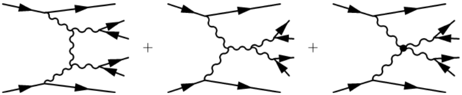


Not separately gauge invariant...

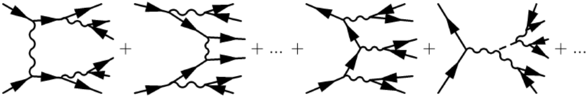
Two classes of processes:

Electroweak production

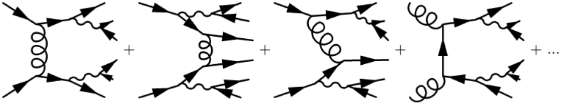
- **VBS signal**



- Purely EW processes



Strong production



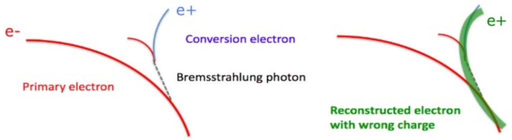
Aim of 8 TeV analysis: finding evidence for same-sign W-boson EW production

Why *same-sign*?

	$W^{\pm}W^{\mp}jj$	$W^{\pm}W^{\pm}jj$
σ_{EW} [fb^{-1}]	91.3	19.5
σ_{QCD} [fb^{-1}]	3030	18.8
σ_{EW}/σ_{QCD}	0.03	1.03

$\longrightarrow$ Background from QCD production reduced

BUT we have **charge mis-identification**!



Charge misID rate

- $Z/\gamma^{*} \rightarrow e^{\pm}e^{\mp}$ events
- used to weight OS events

ATLAS analysis in a nutshell

Evidence for Electroweak Production of $W^{\pm}W^{\pm}jj$ in pp collisions at $\sqrt{s}$ =8 TeV with the ATLAS detector

(http://arxiv.org/pdf/1405.6241v2.pdf)

$\mathcal{L}_{int}$ =20 fb^{-1}, data collected in 2012.
Cut and count analysis in 2 different regions

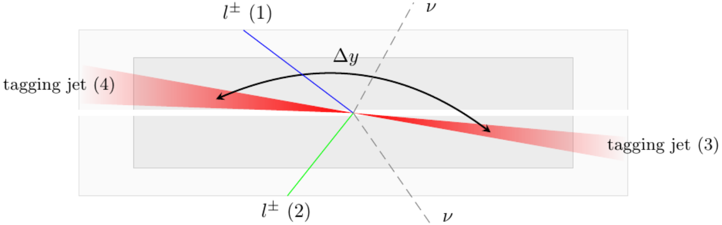
↓

The two analysis regions

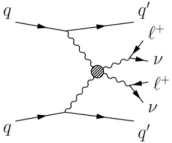
- **Inclusive region**:
  - study $W^{\pm}W^{\pm}$ existence
  - signal = EW + QCD
- **VBS region**:
  - study $W^{\pm}W^{\pm}$ EW production
  - signal = EW, background = QCD

Fiducial regions

Theoretical calculations



- **Inclusive region**
  - m_{jj} (highest p_T jets) > 500 GeV
- **VBS region**
  - + rapidity cut $|\Delta y_{jj}| > 2.4$



$$\sigma^{incl}_{exp}(EW + QCD) = 1.52 \pm 0.11 \text{ fb}$$

$$\sigma^{VBS}_{exp}(EW + INTERF) = 0.95 \pm 0.06 \text{ fb}$$

Calculations made with POWHEG-BOX

Background

Sources

SM processes can mimic the signature $\ell\ell' + E_T^{miss}$+2 jets

Type	Sources	Reduction
1 SS leptons	WZ+jets ZZ+jets $t\bar{t}V$	veto[1] on third lepton
2 OS charge misID	$t\bar{t} \to \ell\nu\ell\nu b\bar{b}$ $W^{\pm}W^{\mp}$ + jets Z/γ^*+jets$\to \ell^{\pm}\ell^{\mp}$+jets	b-jet veto +SS req. large E_T^{miss}+m_Z peak excl.
3 Jets, γ mis-reco	W+jets $t\bar{t} \to \ell\nu jjb\bar{b}$ single top $W\gamma$+jets	b-jet veto+E_T^{miss} tight isolation+veto[1] on third lepton

Estimation:

2 Charge mis-identification: Z events

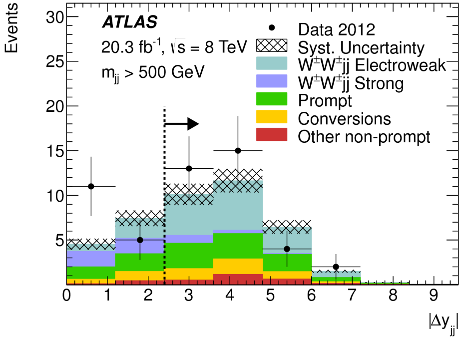
3 Jet fake rate: different control regions

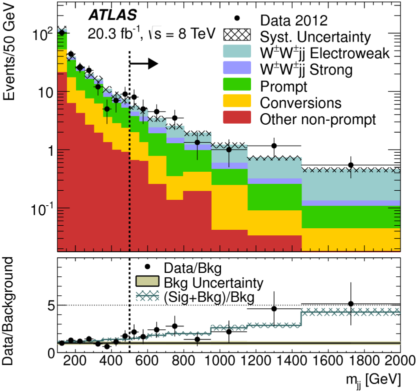
[1]veto: event removed if additional lepton passes looser isolation requirements, p_T >7(6) GeV for e (μ)

Results

Yields

	Inclusive region			VBS region		
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
$W^\pm W^\pm jj$ QCD	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^\pm W^\pm jj$ EW	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total background	6.8 ±1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10



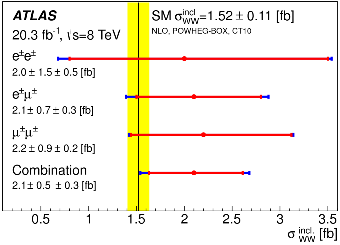


Results

Cross section

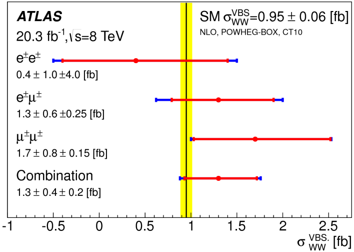
$\sigma^{fid}_{incl} = 2.1 \pm 0.5 \text{ (stat)} \pm 0.3 \text{ (syst) fb}$

- Significance: 4.5σ
- $\sigma_{exp} = 1.52 \pm 0.11$ fb



$\sigma^{fid}_{VBS} = 1.3 \pm 0.4 \text{ (stat)} \pm 0.2 \text{ (syst) fb}$

- Significance: 3.6σ
- $\sigma_{exp} = 0.95 \pm 0.06$ fb



First evidence for $W^{\pm}W^{\pm}jj$ production and EW-only $W^{\pm}W^{\pm}jj$ production

Towards Run 2

LHC Run 2 is approaching:
center of mass energies of 13 TeV are expected

↓

How much is our signal changing between 8 and 13 TeV?

↓

Comparison plots for EW and QCD signal samples at 8 and 13 TeV:

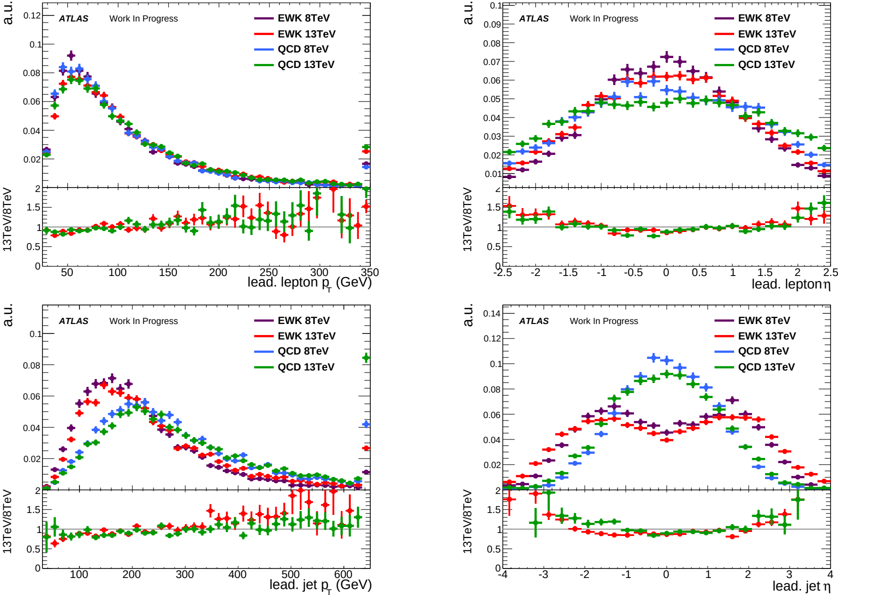
- shapes and acceptance changes?

Technicalities:

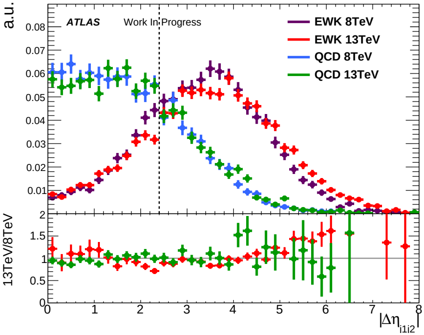
- Signal samples generated with Sherpa 2.1.1, LO up to 3 additional partons

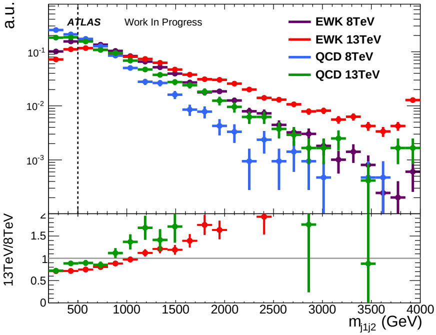
	QCD			EW		
	8 TeV	13 TeV	13 TeV/8 TeV	8 TeV	13 TeV	13 TeV/8 TeV
σ_{prod} [fb]	10.1	25.9	2.6	16.4	43.0	2.6

Signal plot comparison



Acceptance





	EW			QCD		
Cut	8 TeV	13 TeV	13 TeV/8 TeV	8 TeV	13 TeV	13 TeV/8 TeV
All	12.6%	14.3%	1.1	14.1%	13.4 %	1.0
m_{jj}	4.9%	7.2%	1.5	3.7 %	4.8%	1.3
$\Delta\eta_{jj}$	3.7%	5.6%	1.5	1.1 %	1.5%	1.4

An interesting variable

Other variables currently being studied to enhance the signal yield

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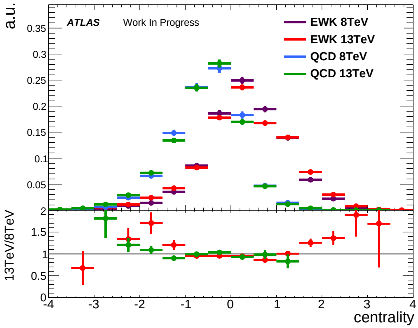
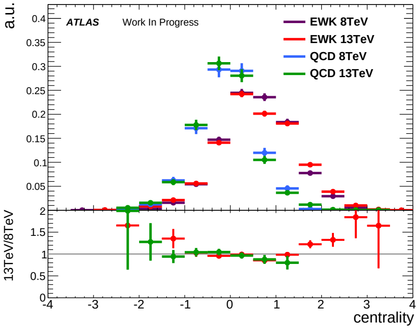
Centrality:
leptons between the two jets

Inclusive region



VBS region



Conclusions and outlook

- The 8 TeV analysis has shown the first evidence of $W^{\pm}W^{\pm}jj$ production

The prospects for the 13 TeV analysis are good!

$\downarrow$

- Higher cross section
- increasing acceptance

BACKUP

Object Reconstruction in ATLAS

Electron candidates:

- combination of a cluster of energy deposit in the em calorimeter and a track in the ID
- $p_T > 25$ GeV
- $|\eta| < 2.47$

Muon candidates

- Tracks in the ID and MS
- $p_T > 25$ GeV
- $|\eta| < 2.4$
- Required to originate from the same interaction vertex
- Cone size of calorimeter and tracker isolation: $\Delta R = 0.3$

Jets

- anti-k_t algorithm with R=0.4
- $p_T > 30$ GeV
- $|\eta| < 4.5$

E_T^{miss}

- Energy collected by em and hadronic calorimeters, muon tracks in the ID and MS

Why same sign?

Opposite-sign production EW diagrams is small compared to QCD one, while in same-sign production they are comparable.
The background from diboson production, $t\bar{t}$ and Z+jets is much lower.

Final state	Process	VVjj-EW	VVjj-QCD
$\ell^{\pm}\nu\ell'^{\pm}\nu' jj$ (same sign, arbitrary flavor)	$W^{\pm}W^{\pm}$	19.5 fb	18.8 fb
$\ell^{\pm}\nu\ell'^{\mp}\nu' jj$ (opposite sign)	$W^{\pm}W^{\mp}$	91.3 fb	3030 fb
$\ell^{+}\ell^{-}\nu'\nu' jj$	ZZ	2.4 fb	162 fb
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\nu' jj$	$W^{\pm}Z$	30.2 fb	687 fb
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\ell'^{\mp} jj$	ZZ	1.5 fb	106 fb

Why VBS studies?

In the absence of a light SM Higgs boson the longitudinally polarized VBS amplitude increases as function of $\sqrt{s}$ and **violates unitarity** at energies around 1 TeV.

↓

The SM Higgs boson should avoid this problem

VV scattering is the key process to probe EWSB

We can establish if the Higgs boson can preserve unitarity of the VBS at all energies

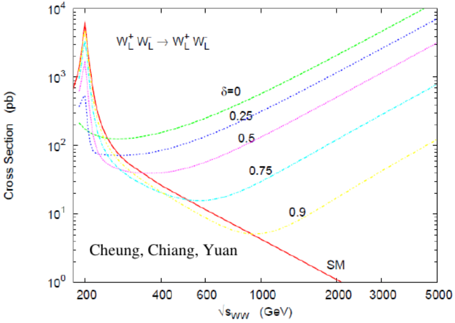
- Test of the Higgs boson nature
  - The discovered Higgs boson contribute fully to the EWSB

    ↓

    VV interaction remain weak at high energies
- Model independent research of alternative theory
  - The discovered Higgs boson is partially responsible for the EWSB

    ↓

    VV interaction get strong at high energy



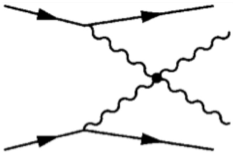
What is VBS?

At hadron colliders VBS can be idealized as

Interaction of gauge bosons radiated from initial state quarks yielding a **final state with 6 particles** (at LO): 4 decay products of the two final vector bosons and two outgoing jets

$\downarrow$

$VVjj$



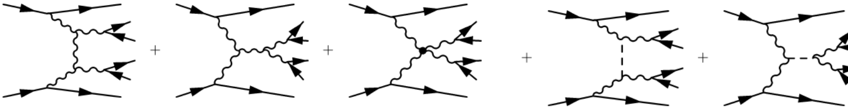
BUT

VBS diagrams are not separately gauge invariant and must be studied in conjunction with additional Feynman diagrams leading to the same VVjj final state.

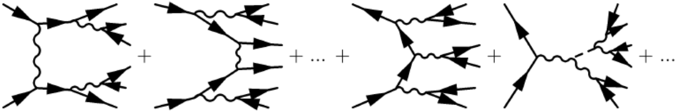
VVjj final state diagrams

Theoretically there are **two classes** of physical processes.

- *Electroweak production*: Only Weak interaction
  - $O(\alpha_{EW}^6)$
  - VBS signal in it



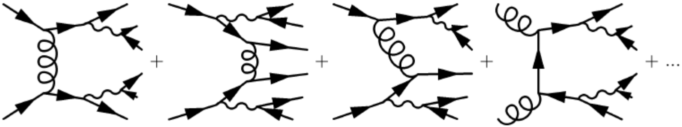
  - It contains also:
    purely ew process which give the same final state
    processes with 3 decaying vector boson (only 1 decaying hadronically)



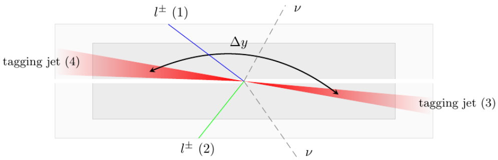
VVjj final state diagrams

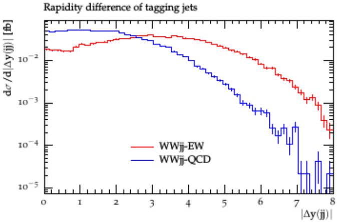
Theoretically there are **two classes** of physical processes.

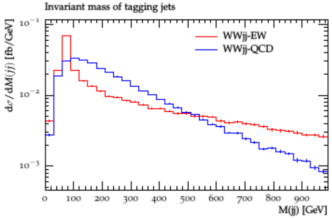
- *Electroweak production*: Only Weak interaction
- *Strong production*: Both strong and ew interaction
  - $O(\alpha_{EW}^4 \alpha_S^2)$
  - *qq* or *gg* scattering + VV radiation
    ew VV production + radiation of gluons leading to jets



How's it made?







VBS topology:

- 2 high-p_T jets in the forward regions (2 jets with highest p_T)
- No color exchange in the hard scattering process → rapidity gap in the central part of the detector
- large m_{jj} and m_{6f}

Monte Carlo samples

- Signal and diboson
  → SHERPA. For VVjj-EW $O(\alpha_{EW})$= 6, for VVjj-QCD $O(\alpha_{EW})$= 4. $O(\alpha_S)$ not fixed but determined by SHERPA
- DBS
  → PYTHIA
- $t\bar{t}$+V (V=W,Z)
  → MADGRAPH, showered by PYTHIA
- Wγ, Z+jets
  → Alpgen, Herwig++ for showering, Jimmy for underlying event modelling
- Parton distribution functions
  → CT10

Yields

	Inclusive SR ee	Inclusive SR $e\mu$	Inclusive SR $\mu\mu$
Other non-prompt	0.61±0.30	1.85±0.76	0.41±0.22
Charge-misID (DD)	2.07±0.38	0.77±0.27	$0.00\pm^{0.00}_{0.00}$
WZ(EW+QCD)	2.74±0.64	5.64±1.25	2.42±0.57
W+γ	1.11±0.61	1.59±0.78	$0.00\pm^{0.00}_{0.00}$
ZZ→4l	0.09±0.07	0.16±0.13	0.07±0.05
$t\bar{t}$+W/Z	0.15±0.06	0.25±0.10	0.11±0.05
Background	6.76±1.16	10.27±1.95	3.01±0.63
$W^{\pm}W^{\pm}$jj	3.96±0.41	11.43±1.11	6.29±0.62
Total Predicted	10.72±1.38	21.71±2.64	9.30±1.03
Data	12.00±3.46(stat.)	26.00±5.10(stat.)	12.00±3.46(stat.)

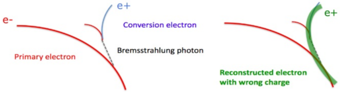
	VBS SR ee	VBS SR $e\mu$	VBS SR $\mu\mu$
Other non-prompt	0.50±0.26	1.50±0.62	0.34±0.19
Charge-misID (DD)	1.39±0.27	0.64±0.24	$0.00\pm^{0.00}_{0.00}$
$W^{\pm}W^{\pm}$jj (strong)	0.25±0.06	0.71±0.14	0.38±0.08
WZ(EW+QCD)	2.06±0.53	4.05±0.98	1.83±0.47
W+γ	0.71±0.43	1.28±0.67	$0.00\pm^{0.00}_{0.00}$
ZZ→4l	0.04±0.04	0.05±0.04	0.01±0.01
$t\bar{t}$+W/Z	0.05±0.03	0.10±0.04	0.02±0.01
Background	5.01±0.91	8.33±1.63	2.58±0.53
$W^{\pm}W^{\pm}$jj (electroweak)	2.55±0.25	7.27±0.64	4.04±0.37
Total Predicted	7.57±1.03	15.59±2.00	6.63±0.76
Data	6.00±2.45(stat.)	18.00±4.24(stat.)	10.00±3.16(stat.)

	Inclusive Region			VBS Region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	–	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^{\pm}W^{\pm}jj$ Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^{\pm}W^{\pm}jj$ Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10

Charge mis-ID background

$\mu^{\pm}$ charge flip rate negligible compared to the $e^{\pm}$

Main process:
radiation of hard photon through Bremsstrahlung emission
followed by $e^{+}e^{-}$ production



$\rightarrow$ **Measurement of the charge misID rate with $Z/\gamma^{*} \rightarrow e^{\pm}e^{\mp}$ events with two methods:**

Likelihood method

$$ln\mathcal{L}(\epsilon|N, N_{SS}) = \Sigma_{i,j} ln\left(N^{i,j}\left(\epsilon_i + \epsilon_j\right)\right) \cdot N_{SS}^{i,j} - N^{i,j}\left(\epsilon_i + \epsilon_j\right)$$

$N^{i,j}$ total number of candidate
$N_{SS}^{i,j}$ number of candidates with SS e pairs
ϵ probability to undergo charge mis-identification

Tag-and-Probe method

Tag electron defined with tighter cuts $\rightarrow$ charge assumed to be correctly reconstructed
Probe electron additional lepton in each event

$$\epsilon = \frac{N_{probes}^{SS}}{N_{probes}}$$

For both methods:

- ϵ measured as a function of η and p_T of the electron
- Closure tests performed exploiting MC truth

The prediction for the number of SS events originated from charge misID is given by:

OS events selected and weighted by the charge misID rate

Fiducial regions

Theoretical calculations

Two fiducial regions are defined to follow the selections applied in the analysis

- **Inclusive region:**
  - 2 same sign leptons with
    - $p_T > 25$ GeV
    - $|\eta| < 2.5$
    - $m_{\ell\ell} > 20$ GeV
    - $\Delta R_{\ell\ell} = \sqrt{(\Delta\Phi)^2 + (\Delta\eta)^2} > 0.3$
  - At least 2 anti-k_t jets with
    - R = 0.4
    - $p_T > 30$ GeV
    - $|\eta| < 4.5$
    - $\Delta R_{\ell j} > 0.3$
    - m_{jj} (highest p_T jets) > 500 GeV
  - $E_T^{miss} > 40$ GeV
- **VBS region**: cuts above + rapidity cut $|\Delta y_{jj}| > 2.4$

ATLAS analysis event selection

Summary

Events selection used for the analysis:

- event cleaning
- exactly two selected leptons with $m_{\ell\ell} > 20$ GeV
- veto events with additional veto leptons
- $q_{\ell_1} \times q_{\ell_2} > 0$
- $p_T > 25$ GeV
- $|m_{\ell\ell} - m_Z| > 10$ GeV in the *ee* channel
- $E_T^{miss} \geq 40$ GeV
- at least two jets with $p_T > 30$ GeV and $|\eta| < 4.5$
- *b*-jet veto
- $m_{jj} > 500$ GeV
- $|\Delta y_{jj}| > 2.4$ - VBS analysis region

Samples generation cuts

Process:

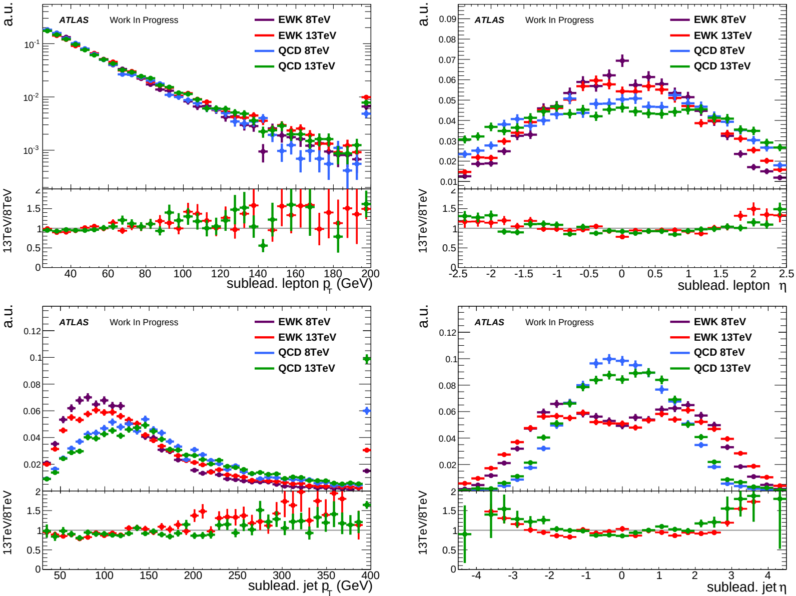
$W^{\pm}W^{\pm}jj(j)$

- leptons:
  - $p_T > 5$ GeV
  - no η cut
- jets:
  - N$\geq$2
  - $p_T > 15$GeV

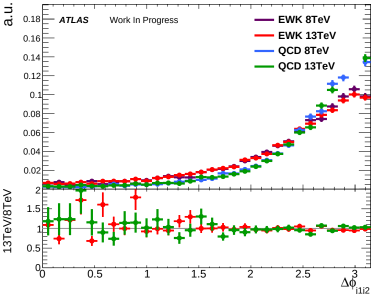
Signal plots cutflow

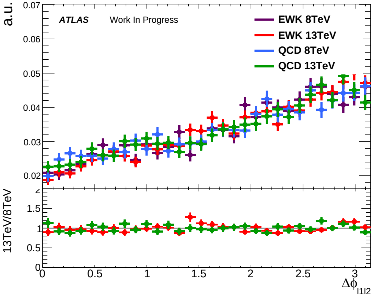
- p_T^{lep} >25 GeV
- $|\eta^{lep}|$ <2.5 GeV
- $m_{\ell\ell} > 20$ GeV
- $q_{\ell_1} \times q_{\ell_2} > 0$
- $E_T^{miss} \geq 40$ GeV
- $p_T^j > 30$ GeV
- $|\eta|^j < 4.5$
- $m_{jj} > 500$ GeV
- $|\Delta y_{jj}| > 2.4$ - VBS analysis region

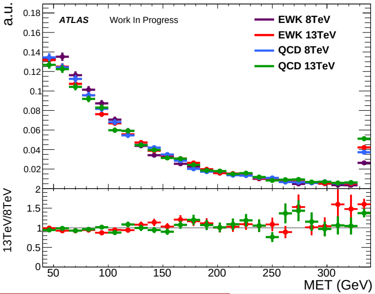
More plots

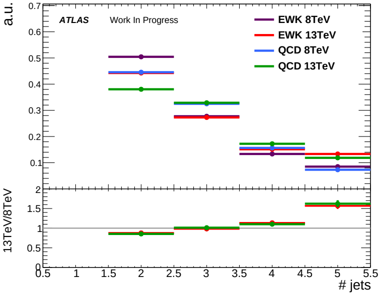

ATLAS Work In Progress
EWK 8TeV
EWK 13TeV
QCD 8TeV
QCD 13TeV
a.u.
13TeV/8TeV
sublead. lepton p_T (GeV)
sublead. lepton η
sublead. jet p_T (GeV)
sublead. jet η

More plots


ATLAS Work In Progress
EWK 8TeV
EWK 13TeV
QCD 8TeV
QCD 13TeV
a.u.
13TeV/8TeV
$\Delta\phi_{j1j2}$


ATLAS Work In Progress
EWK 8TeV
EWK 13TeV
QCD 8TeV
QCD 13TeV
a.u.
13TeV/8TeV
$\Delta\phi_{l1l2}$


ATLAS Work In Progress
EWK 8TeV
EWK 13TeV
QCD 8TeV
QCD 13TeV
a.u.
13TeV/8TeV
MET (GeV)


ATLAS Work In Progress
EWK 8TeV
EWK 13TeV
QCD 8TeV
QCD 13TeV
a.u.
13TeV/8TeV
jets

Centrality

Defined as:

$$\zeta = min(min(\eta_{\ell 1}, \eta_{\ell 2}) - min(\eta_{j1}, \eta_{j2}),\ max(\eta_{j1}, \eta_{j2}) - max(\eta_{\ell 1}, \eta_{\ell 2}))$$